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AD A123760

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TECHNICAL REPORT ARLCB-TR-82030

FRACTURE TOUGHNESS OF HIGH STRENGTH STEEL PREDICTED FROM CHARPY ENERGY OR REDUCTION-IN-AREA

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DECEMBER 1982

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARLCB-TR-82030	2. GOVT ACCESSION NO. AD-A123 760	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FRACTURE TOUGHNESS OF HIGH STRENGTH STEEL PREDICTED FROM CHARPY ENERGY OR REDUCTION-IN-AREA		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. H. Underwood and G. S. Leger		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Armament Research & Development Command Benet Weapons Laboratory, DRDAR-LCB-TL Watervliet, NY 12189		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 72801213000 PRON No. 1A1258731A1A
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command Large Caliber Weapon Systems Laboratory Dover, NJ 07801		12. REPORT DATE December 1982 13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at 15th National Symposium on Fracture Mechanics, ASTM, University of Maryland in College Park, MD, 7-9 July 1982.
Published in proceedings of the symposium.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture Toughness
Alloy Steel
Statistical Analysis
Mechanical Tests
Forged Cylinders

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Analysis is presented of the results of an extensive mechanical and fracture test program. Ninety-six hollow cylinder forgings of A723 steel with five different manufacturing processes were tested at two locations with different outer diameters. Yield strength, plane-strain fracture toughness, Charpy impact energy, and tensile reduction-in-area were measured and analyzed for statistical variation and difference of mean value. Linear regression was

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20. ABSTRACT (CONT'D)

used to fit lines to the data and to determine correlation coefficients. Conclusions were drawn as to the suitability of Charpy energy and reduction-in-area as predictors of plane-strain fracture toughness.

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ACKNOWLEDGEMENTS

We gratefully acknowledge the work of F. A. Heiser who planned and directed the testing program described here and E. E. Coppola who provided advice on statistical analyses.

INTRODUCTION

The energy to failure in a v-notched Charpy impact test and the percentage reduction-in-area in a tensile test are often used as indicators of fracture toughness for steels. Seldom is enough testing performed to rate with statistical significance how well these two tests predict fracture toughness. This report describes an extensive series of tests the results of which were analyzed to obtain such a rating. It is not the purpose here to establish a specific correlation between Charpy energy or reduction-in-area and fracture toughness, but rather to determine, using statistical methods, just how well each of these tests can predict fracture toughness.

Charpy energy and reduction-in-area, along with yield strength, have been the primary material acceptance tests for Army cannon forgings for many years. Plane-strain fracture toughness is now generally recognized as a basic material property for quantitative description of crack-related failure. It is now used in design and prototype development of cannons, whereas the simpler Charpy energy and reduction-in-area tests are used for production material acceptance. Only about one tenth the time is required for either of these tests, compared to that for plane-strain fracture toughness. So the prediction of plane-strain fracture toughness by using the simpler tests is important.

Appreciation of the importance of fracture toughness to the function of cannons is useful background for this report. Some such appreciation can follow from a review of failure processes often observed in cannons. Figure 1

shows a section of a cannon tube[1] which failed following actual and then simulated firing. The erosion and heat checking processes which damage the inner surface are not known to be related to fracture toughness, but these are the processes which often initate crack-related failure. A particularly severe case of erosion of the inner surface is shown in Figure 1. For the fracture surface in the photo, erosion serves to initiate the fatigue crack growth, which then occurs in the characteristic semi-elliptical crack shape. Fracture toughness has an important effect on fatigue cracking, particularly in high stress, low cycle fatigue which usually is the loading condition for a cannon. As the maximum applied stress intensity factor, K_I, during the fatigue cycle becomes nearly equal in value to the plane-strain fracture toughness, K_{Ic}, of the material, the rate of fatigue crack growth becomes higher than the usual relation between applied K_I and growth rate.[2] Further, if the ratio of K_{Ic} to yield strength, σ_{ys}, is small enough, then the area of plastic deformation relative to specimen size is small and a fast fracture will occur as the final fracture event. The final fracture will be a classic brittle fracture only in the extreme condition of a very small ratio, K_{Ic}/σ_{ys}. Fortunately, it is more typical that the final breakthrough to the tube outer surface occurs in a relatively confined area of the tube, as shown in Figure

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[1]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Predictions, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

[2]Paris, P. C., Bucci, R. J., Wessel, E. J., Clark, W. R., and Mager, T. R., "Extensive Study of Low Cycle Fatigue Crack Growth Rates in A533 and A508 Steels," Stress Analysis and Growth of Cracks, ASTM STP 513, American Society for Testing and Materials, 1972, pp. 141-176.

1. This results in a leak rather than a break up of the tube, which is the desired leak-before-break condition. The nature of the final fast fracture is highly dependent on the material fracture toughness.

Approach and Objective

Fracture toughness, Charpy energy, and tensile tests were performed using specimens from both ends of cannon forgings. The test results were analyzed to determine quantitatively how good a prediction of fracture toughness can be obtained from the Charpy energy and reduction-in-area tests. The predictive ability of the two tests was determined by comparing results from opposite ends of the forging which have clearly defined differences in fracture toughness due to manufacturing process variables. A statistical test for different mean values was used to measure the ability of the two mechanical tests to differentiate between high and low fracture toughness.

TEST PROCEDURES

Ninety-six cannon forgings were tested as engineering support to cannon tube production. Reference 3 describes some of the results and analyses of the tests. Only certain details will be described here. The forgings were hollow cylinders, about 220 in. (5.6 m) long*, 3.5 in. (89 mm) inner diameter, 6.7 in. (170 mm) outer diameter at the muzzle end of the forging and 9.4 in. (239 mm) outer diameter at the breech end of the forging. The composition of

[3]Tauscher, S., "The Correlation of Fracture Toughness With Charpy V-Notch Impact Test Data," USA ARRADCOM Technical Report No. ARLCB-TR-81012, Benet Weapons Laboratory, Watervliet, NY, March 1981.

*The original tests and analyses were performed with English units, so they are the primary units used.

the steel was that of ASTM Specification for Alloy Steel Forgings for High-Strength Pressure Component Applications, A723-77, Grade 2, a high strength steel with nickel, chromium, and molybdenum as the primary alloying elements. The forgings were produced using five different forging and heat treatment processes, each with a specified yield strength range of 160-180 ksi (1103-1241 MPa). An outline of these processes is listed in Table I. Some additional information is given in prior work.[3] The important point here is that extensive testing was performed using 18 or 20 forgings produced by each of five significantly different production processes. These test results provide excellent data with which to compare the ability of Charpy energy and reduction-in-area to predict fracture toughness. One indication of the high consistency of the production processes is the small variation of yield strength as listed in Table I. The largest standard deviation of yield strength for the nine subgroups of results is 1.9 percent of the mean value, and the largest difference between subgroup mean value and grand mean value is 3.2 percent.

The fracture toughness tests were performed at +70°F (+21°C) following ASTM Method for Plane-Strain Fracture Toughness of Metallic Materials, E399-81 whenever possible. The arc specimen was used in the C-R orientation*, as sketched in Figure 1. Thicknesses of 1.0 and 1.5 in. (25 and 38 mm) were

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[3]Tauscher, S., "The Correlation of Fracture Toughness With Charpy V-Notch Impact Test Data," USA ARRADCOM Technical Report No. ARLCB-TR-81012, Benet Weapons Laboratory, Watervliet, NY, March 1981.

*The C-R orientation is that with the crack plane normal to the circumferential direction and crack growth in the radial direction.

TABLE I. TEST CONDITIONS

Process	Number of Forgings	Location	Yield Strength, 0.1% Offset, ksi (MPa) Mean	Std. Deviation
#1; Electro-slag refined, supplier A, rotary forged	20	Muzzle	165.8 (1143)	3.1 (25)
		Breech	172.8 (1191)	3.0 (24)
#2; Vacuum degassed, supplier A, rotary forged	20	Muzzle	170.4 (1175)	2.2 (17)
		Breech	173.5 (1196)	2.3 (18)
#3; Vacuum degassed, supplier B, rotary forged	20	Muzzle	164.9 (1137)	2.2 (17)
		Breech	166.0 (1145)	1.6 (13)
#4 Vacuum degassed, supplier A, press forged	18	Breech	168.3 (1160)	2.3 (18)
#5 Vacuum degassed, supplier B, press forged	18	Muzzle	165.0 (1138)	1.3 (10)
		Breech	165.8 (1143)	1.7 (13)
		Grand Mean	168.1 (1159)	

used for muzzle and breech specimens, respectively. Two requirements of Method E-399 were sometimes not met. They are the size requirement and the maximum load requirement. The size requirement is that the crack length and the specimen thickness be at least equal to 2.5 $(K_{Ic}/\sigma_{ys})^2$. The actual crack lengths and thicknesses varied from 1.6 to 3.0 $(K_{Ic}/\sigma_{ys})^2$ and averaged $2.5(K_{Ic}/\sigma_{ys})^2$. The maximum load requirement is that P_{max}/P_5 be at most 1.0, where P_{max} is the maximum load during the test and P_5 is the intercept load for a line with the elastic slope less five percent. The actual ratio P_{max}/P_5 varied from 1.00 to 1.13 and averaged 1.05. Only twelve of the nearly two hundred test values of P_{max}/P_5 were over 1.10. Since the tests were not in general violation of the size and maximum load requirements, we believe that the K_{Ic} results in this report are good measurements of plane-strain fracture toughness.

The Charpy energy tests were performed at -40°F (-40°C) in the C-R orientation, following ASTM Methods for Notched Bar Impact Testing of Metallic Materials, E23-81. The reason for the difference in test temperature between Charpy energy and fracture toughness tests is based on practical considerations. Since Charpy energy is measured from every production component and it is nearly as simple at low temperature as at room temperature, it is performed at -40°F (-40°C), a typical low service temperature. The more complex fracture toughness test is performed at low temperature only occasionally.

The tension tests were performed at +70°F (+21°C) in the C orientation using a 0.357 in. (9.1 mm) diameter specimen, following ASTM Methods for Tension Testing of Metallic Materials, E8-81. Only the yield strength and

reduction-in-area results from the tension tests are considered in this report.

RESULTS AND ANALYSIS

Frequency Distributions

Frequency distribution plots of all fracture toughness, K_{Ic}, Charpy energy, CVN, and reduction-in-area, RA, data considered here are shown in Figures 2, 3, and 4. Each data point is the average of two measured test values. This averaging procedure was used throughout the analyses and reporting of the data, because any given single measured value could be associated only with a 1.0 or 1.5 in. (25 or 38 mm) thick section from a certain end of a forging, not a particular location within that section. Since location within a section was not known, the two measured values were averaged. At most there are ninety-six data points in the frequency distributions, usually less because of occasional missing data. A separate frequency distribution was plotted for the muzzle and breech ends of the forgings, because the outer diameters are significantly different in size, which is an indication of basic differences in both forging and heat treatment processes.

Two observations can be made at first viewing of the frequency distributions. First, the largest difference in mean values between muzzle and breech results seems to be with K_{Ic}. Second, the least normal distributions seem to be the CVN distributions, for both muzzle and breech. Upcoming analysis will show that these observations are significant and can be well described quantitatively using statistical tests.

Statistical analysis is simpler if the data are normally distributed. The Kolmogorov-Smirnov test, an accepted method for checking for a normal distribution,[4] was applied to the six sets of data of Figures 2, 3, and 4. The test is a comparison of the actual probability distribution from the measured data with the ideal normal probability distribution having the same mean and standard deviation. If the maximum deviation of the measured distribution from the ideal normal distribution is less than a certain amount for the given sample size, then the measured data can be considered to be normally distributed. Figures 5 and 6 compare the measured with the ideal normal probability distributions for the muzzle K_{Ic} and CVN data, respectively. The maximum deviations are 0.039 and 0.138, respectively, in dimensionless probability units. These are to be compared with 0.182, the maximum allowed value[4] for the sample size of 78 in Figures 5 and 6 and for a 99 percent confidence level. This comparison shows that both sets of data are normally distributed. In addition, the observation discussed previously, that the CVN distributions appear to be the least normal, is verified by the larger deviation from a normal probability distribution. One reason for this deviation from normal distribution is the fact that CVN distribution is truncated because of rejection of forgings with CVN values below a minimum requirement. Such rejections cause an abrupt drop in probability as the required minimum, 15 ft-lb (20.4 Nm), is approached. This abrupt drop in CVN frequency and probability can be seen in Figures 4 and 6, respectively.

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[4]Bowker, A. H. and Lieberman, G. J., Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1972, pp. 454-458.

The overall results of the tests for normalcy are that the K_{Ic} data are closest to an ideal normal distribution, the RA data are intermediate, and the CVN data are the least normal. All six groups of data pass the Kolmogorov-Smirnov test for normalcy.

Probability of Different Means

A statistical summary of all test results is presented in Table II. Each mean and standard deviation was calculated using nominally twenty average values from forty tests, as described in the foregoing section on test procedures. The standard deviation relative to mean averages about six percent for K_{Ic}, nine percent for RA, and twelve percent for CVN, compared with one to two percent for yield strength, from Table I. These differences in variation of the test results have an effect on how well CVN or RA can predict K_{Ic}, as will be discussed in the upcoming paragraph.

There appear to be significant differences in K_{Ic} between muzzle and breech location for each of the four processes for which comparison data were available. The probability of different means statistical test was used to quantify this difference in K_{Ic} and to determine if CVN or RA can detect a difference depending on location. In basic concept the probability of different means depends on (a) the difference between the two mean values, and (b) the amount of variation about both mean values. A dimensionless test statistic, d, was calculated as[5]

$$d = \frac{|\mu_M - \mu_B|}{(\sigma_M^2+\sigma_B^2)^{1/2}} \qquad (1)$$

[5]Bowker, A. H. and Lieberman, G. J., Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1972, pp. 225-230.

TABLE II. SUMMARY OF FRACTURE TOUGHNESS, CHARPY ENERGY, AND REDUCTION-IN-AREA TEST RESULTS

Process; Location	Fracture Toughness, K_{Ic} μ $ksi \cdot m^{1/2}$	μ $(MPa \cdot m^{1/2})$	σ/μ	P	Charpy Energy, CVN μ Ft-Lb	μ (Nm)	σ/μ	P	Reduction-in-Area, RA μ %	σ/μ	P
#1 Muzzle	116.8	(128.0)	.074	0.96	26.7	(36.3)	.135	0.33	47.2	.064	0.50
Breech	130.2	(142.7)	.078		24.5	(33.3)	.118		44.6	.072	
#2 Muzzle	112.7	(123.5)	.077	0.97	19.5	(26.5)	.108	0.34	37.9	.111	0.19
Breech	124.4	(136.3)	.047		21.0	(28.6)	.105		40.1	.097	
#3 Muzzle	96.1	(105.3)	.055	0.99	16.4	(22.3)	.097	0.96	38.6	.093	0.02
Breech	126.3	(138.4)	.059		19.1	(26.0)	.110		38.0	.084	
#4 Breech	134.1	(147.0)	.064	—	29.6	(40.3)	.179	—	46.9	.085	—
#5 Muzzle	107.6	(117.9)	.049	0.99	19.3	(26.2)	.119	0.22	40.8	.061	0.02
Breech	118.0	(129.3)	.039		20.5	(27.9)	.083		41.2	.107	
Average	118.5	(129.9)	.060	0.98	21.8	(29.6)	.117	0.46	41.7	.086	0.18

μ = mean; σ = standard deviation; P = probability of different means.

where μ_M, μ_B and σ_M, σ_B are the mean and standard deviation for muzzle and breech tests, respectively. Relatively large differences in mean and relatively small standard deviations will produce a large value of d and a high probability that the means are statistically different. The value of d was applied to operating characteristic curves[5] for the appropriate sample size, nominally twenty, and confidence level of 99 percent, in order to determine the probability of different means, P, shown in Table II. The P values for the K_{Ic} data confirm the subjective observation that the results differ with location. On average it is 98 percent probable that the K_{Ic} test distinguishes between a high toughness material at the breech end and a lower toughness material at the muzzle end. This compares with the average 46 percent probability that the CVN test can distinguish breech from muzzle and the 18 percent probability that RA can distinguish breech from muzzle.

Results in Table II for two of the five processes should be considered further. The process #1 results show an apparent inconsistency. The average K_{Ic} is lower at the muzzle location than at the breech, whereas the CVN and RA results are higher at the muzzle. However, since the probability of different means is relatively low for these CVN and RA results, this is not a serious inconsistency. The process #3 results show the largest difference in K_{Ic} between muzzle and breech and 99 percent probability of different means. If CVN or RA are to be useful for predicting K_{Ic}, they should be able to distinguish breech from muzzle in this case. The CVN test does well, with a

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[5]Bowker, A. H. and Lieberman, G. J., Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1972, pp. 225-230.

96 percent probability of different means. The RA test does poorly, with a two percent probability of different means and a higher value at the muzzle rather than a lower value as would be expected from the K_{Ic} results.

Correlation

Plots of K_{Ic} versus both CVN and RA for process #1 are shown in Figures 7 and 8 for breech and muzzle data, respectively. Standard linear regression of K_{Ic} on CVN and K_{Ic} on RA was performed on a calculator. The regression lines are shown as the solid lines, with associated correlation coefficients. The dashed lines were calculated with the axes reversed, that is, by linear regression of CVN on K_{Ic} and RA on K_{Ic}. The correlation coefficients are unchanged by the reversal of axes, but, as can be seen, the regression lines are quite different. The reason for the difference is that the solid line is determined by minimizing the square of the difference in K_{Ic} between the data and the line, whereas the dashed line is determined by minimizing the square of the difference in CVN or RA between the data and the line. The solid line, with K_{Ic} as the dependent variable, is the appropriate procedure for making predictions of K_{Ic} by another test result, CVN or RA in this case. With K_{Ic} as the dependent variable the differences in K_{Ic} are minimized, and this is appropriate since K_{Ic} is the known quantity which is being predicted by other tests. However, it should be noted that the appropriate linear regression of K_{Ic} on CVN or RA can result in a straight line which appears to be quite different from an eyeball fit. The solid line in the K_{Ic} versus RA plot in Figure 8 is an example. One reason for this is that an eyeball fit is determined by minimizing the difference between the data point and the line in a direction perpendicular to the line, whereas the differences in linear

regression are seldom in a direction perpendicular to the line.

Plots of K_{Ic} versus CVN and RA, regression lines, and correlation coefficients are shown in Figure 9 for the process #3 data. It is interesting to note that the correlation coefficients for K_{Ic} versus RA, both muzzle and breech locations, are not significantly different from those for K_{Ic} versus CVN, and yet the ability of RA and CVN to distinguish between muzzle and breech are very different. Refer again to Table II, process #3. So similar correlation of RA and CVN with K_{Ic} does not imply that RA and CVN can similarly distinguish between muzzle and breech material.

The correlation coefficients for all data are shown in Table III. The coefficient for each separate subgroup of twenty data points was calculated, as was the coefficient for the combination of the two subgroups into one. In one K_{Ic} versus CVN group, process #1, and in two K_{Ic} versus RA groups, processes #1 and #3, the combined correlation coefficient was significantly lower than either separate coefficient. This shows that improper combination of data can lead to improper prediction of one test result from another, K_{Ic} from CVN or RA in this case. The average values of correlation coefficient included in Table III show that CVN correlates better with K_{Ic} than does RA, and that the reduction in combined correlation coefficient relative to the separate values is less for CVN than for RA.

Barsom and Rolfe[6] described a correlation between CVN and K_{Ic} which should be considered here. It is

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[6]Barsom, J. M. and Rolfe, S. T., "Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition-Temperature Range," Impact Testing of Metals, ASTM STP 466, American Society for Testing and Materials, 1970, pp. 281-302.

TABLE III. CORRELATION OF FRACTURE TOUGHNESS WITH CHARPY ENERGY AND REDUCTION-IN-AREA

Process Location	Correlation Coefficient; K_{Ic} Vs. Charpy Energy Separate	Combined	Correlation Coefficient; K_{Ic} Vs. Reduction-in-Area Separate	Combined
#1 Muzzle	0.83	0.43	0.35	0.12
Breech	0.81		0.57	
#2 Muzzle	0.68	0.71	0.47	0.47
Breech	0.70		0.52	
#3 Muzzle	0.77	0.76	0.64	0.17
Breech	0.64		0.66	
#4 Breech	0.88	--	0.87	--
#5 Muzzle	0.65	0.58	0.05	0.12
Breech	0.44		0.16	
Average	0.71	0.62	0.48	0.22

$$K_{Ic} = (5.0\ CVN\ \sigma_{ys} - 0.25\ \sigma_{ys}^2)^{1/2} \quad (2)$$

in which K_{Ic} is in ksi•in.$^{1/2}$, σ_{ys} is in ksi, and CVN is in ft-lb. Since yield strength, σ_{ys}, varies little in the tests here, as shown in Table II, the most important guidance that can be obtained from the Barsom-Rolfe correlation is that K_{Ic} can be expected to vary with the square root of CVN. This expectation can also be obtained from J integral analysis. For the three-point bend specimen[7]

$$J = 2A/bB \quad (3)$$

where B is specimen thickness, b is uncracked ligament depth, and A is the total energy under the load versus load-point deflection curve, a quantity quite analagous to Charpy energy. Using the relation between J and K for elastic, plane-strain conditions,

$$K = [EJ/(1-\nu^2)]^{1/2} \quad (4)$$

it can be easily shown that K_{Ic} can be expected to vary with the square root of CVN. Based on the above, correlation coefficients for K_{Ic} versus $(CVN)^{1/2}$ and K_{Ic} versus $(RA)^{1/2}$ were calculated for the process #1 results. The coefficients are 0.83, 0.81, 0.35, and 0.58 for CVN and RA muzzle and breech, respectively. Comparing these values with those in Table III for linear correlation with K_{Ic} shows that there is no significant difference between square root and linear correlation of CVN or RA with K_{Ic}.

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[7]Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H., "A Procedure for the Determination of Ductile Fracture Toughness Values Using J Integral Techniques," Journal of Testing and Evaluation, Vol. 7, No. 1, January 1979, pp. 49-56.

Scatter Diagram

Plots of the deviation of the K_{Ic} data points from combined linear regression curves of K_{Ic} versus CVN and K_{Ic} versus RA are shown in Figure 10. The combined regression curves were calculated using both breech and muzzle data and resulted in the combined correlation coefficients of 0.43 and 0.12, shown in Table III for CVN and RA, respectively. The plots of deviations, also called scatter diagrams, provide a graphic display of both the source and the direction of the deviation of the actual data from the fitted line. In the case here it is clear that nearly all the deviation in K_{Ic} above the K_{Ic} versus CVN and K_{Ic} versus RA regression lines is from breech tests, and the deviation below is from muzzle tests. This result is a further clear indication that there is a significant difference between muzzle and breech fracture toughness and that toughness in these two locations must be analyzed separately, as done here.

SUMMARY AND CONCLUSIONS

The statistical distribution and variation of the test results considered here are summarized as K_{Ic} being the most normal and least variable, RA intermediate in both regards, CVN the least normal and most variable. All test results, including the CVN results, passed the Kolmogorov-Smirnov test for a normal distribution. The high variation of the CVN results is related to the specimen configuration. The volume of material which is critically loaded in the Charpy specimen, that is, the material around the notch tip, is the smallest of the three tests. In addition, the Charpy specimen is easily affected by critical configurational variations such as notch root size and

roughness. The configuration of the critical areas of the RA and K_{Ic} specimens, the smooth outer diameter and the fatigue crack tip, respectively, are easier to control than is the CVN notch. The solution to the high variation of the CVN test is to increase the minimum required value or to increase the number of CVN tests. An example of the latter is the requirement in ASTM Specification A723 for three CVN tests, compared with one yield strength test, to test for a given material condition.

The correlation coefficient from linear regression is an important measure of how well one test result can predict another. Regression of K_{Ic} on CVN gives average coefficients of 0.71 and 0.62, for analyses with muzzle and breech separated and combined, respectively. Regression of K_{Ic} on RA gives average coefficients of 0.48 and 0.22, for separate and combined analyses, respectively. The correlation of K_{Ic} with CVN might have been better if the CVN tests had been performed at the temperature of the other tests, +70°F (+21°C), rather than at -40°F (-40°C). The poorer correlation of K_{Ic} with RA is related to a significant extent to the basic differences in the tests. K_{Ic} is a measure of initial growth of a preexisting crack with limited plastic deformation, whereas RA is a measure of considerable tensile plastic deformation of a smooth specimen which precedes internal crack initiation and failure. It is concluded that, for the conditions of the tests here, the best prediction of K_{Ic} would be from regression of K_{Ic} on CVN using representative data from a single manufacturing process and a single location within the forging. This procedure will give a good estimate of K_{Ic} from measured values of CVN, provided that enough repeat measurements are performed to account for the variability of the CVN test.

Probability of different means analysis is a valuable complement to correlation analysis for determining how well one test result can predict another. Probability of different means is particularly useful, in the case here, for determining whether or not there is a significant difference in K_{Ic} between two material conditions based on the available CVN or RA data. Comparison of the results in Tables II and III shows that CVN or RA predicts the same trend as K_{Ic} when (a) the probability of different means of CVN or RA is high and (b) the combined correlation coefficient of K_{Ic} versus CVN or RA is high. The four highest P values for CVN and RA, in which also the breech value of CVN or RA is higher than the muzzle value, are 96, 34, 22, and 19 percent, for CVN process #3, #2, #5, and RA process #2, respectively. These subgroups also result in the highest combined correlation coefficients and in the same order, 0.76, 0.71, 0.58, and 0.47, respectively. It is concluded that for the conditions of the tests here, the best determination of a significant difference in K_{Ic} between two material conditions is by the probability of different means of the associated CVN data.

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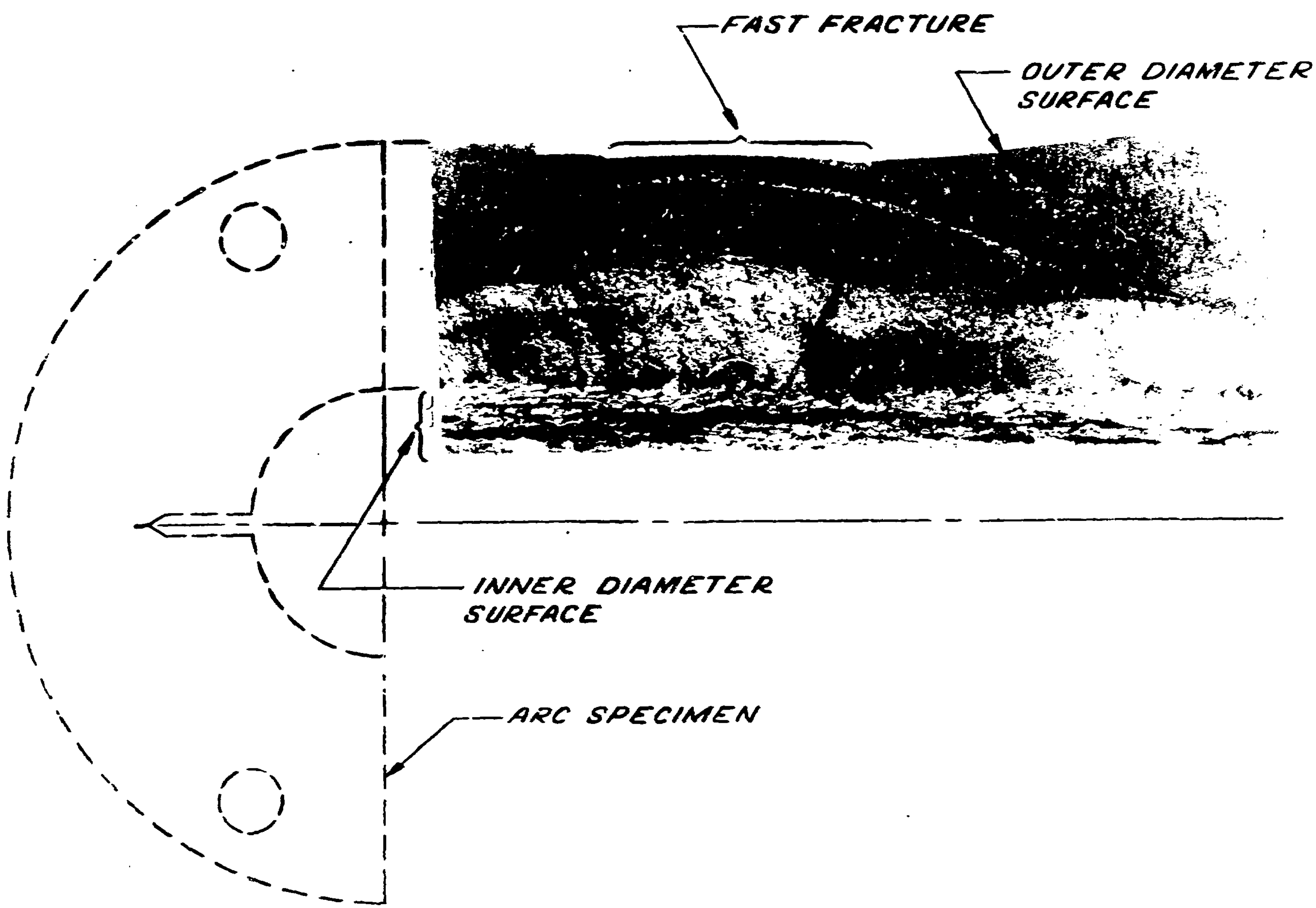

Figure 1. Fracture Surface of Cannon Tube Following Actual and Simulated Firing, Along With Sketch of Arc Specimen Used For Fracture Toughness Testing.

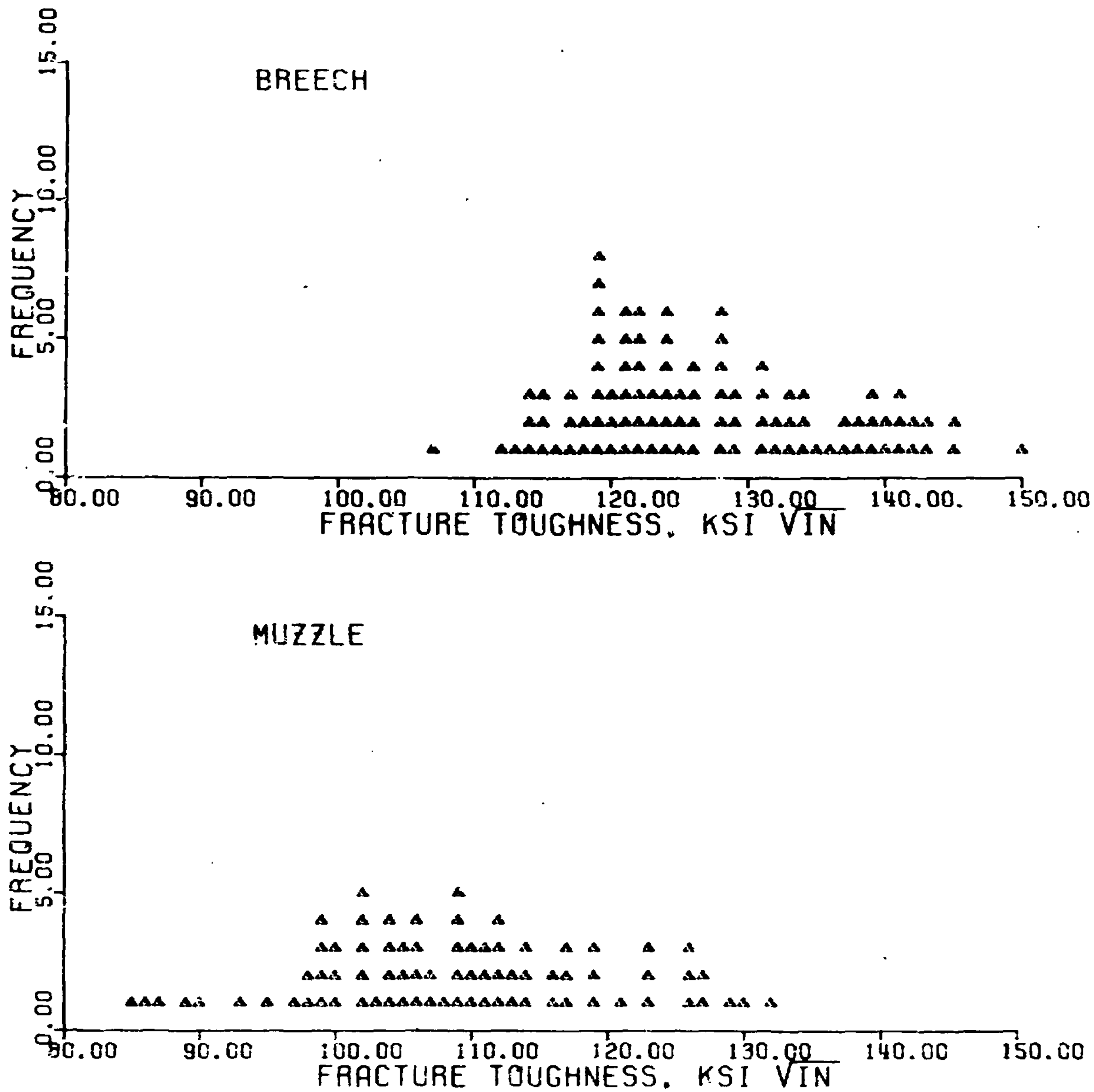

Figure 2. Frequency Versus Fracture Toughness From Cannon Forgings; Muzzle and Breech Locations; ksi·in.$^{1/2}$ x 1.10 = MPa·m$^{1/2}$.

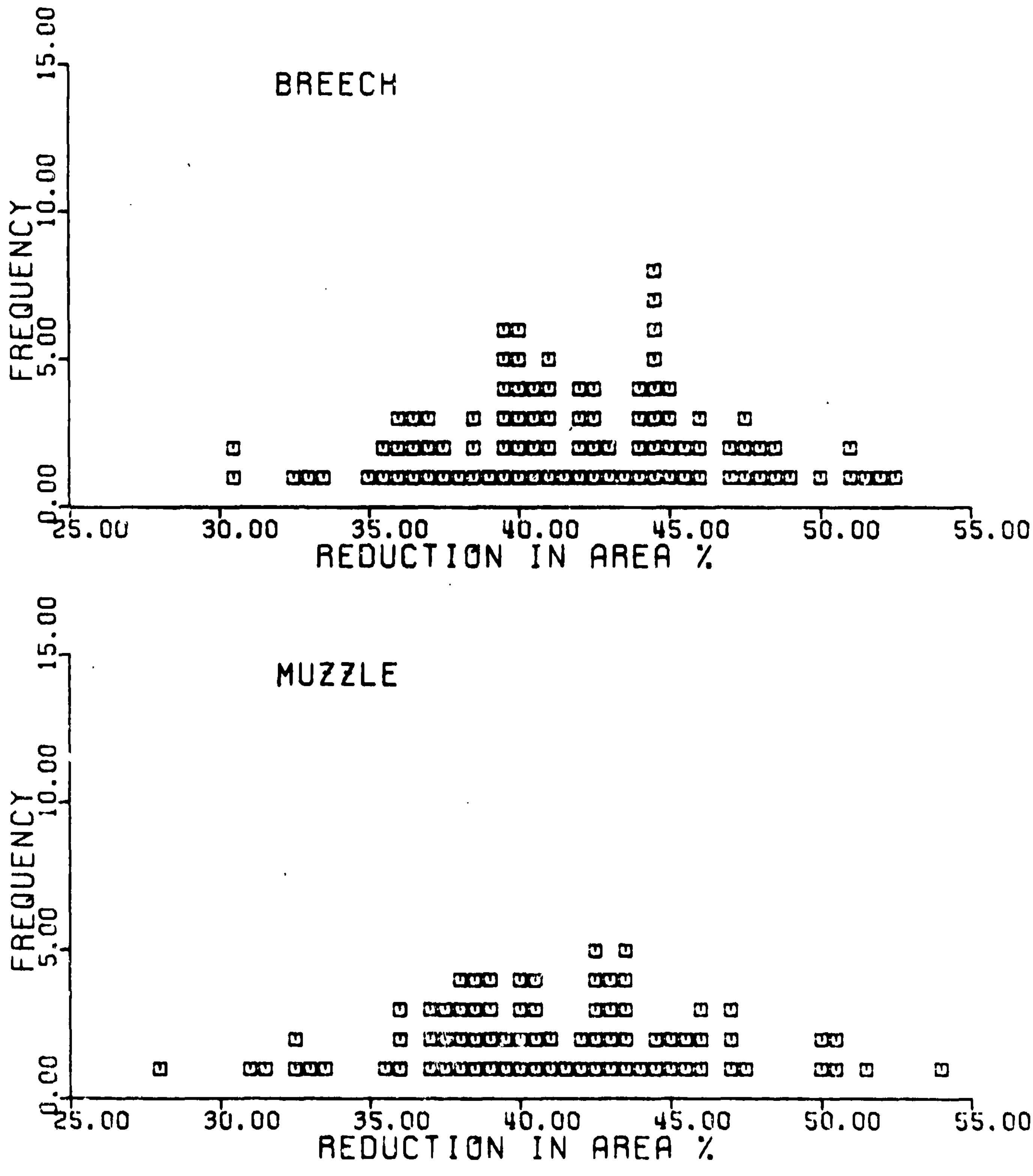

Figure 3. Frequency Versus Reduction-in-Area From Cannon Forgings; Muzzle and Breech Locations.

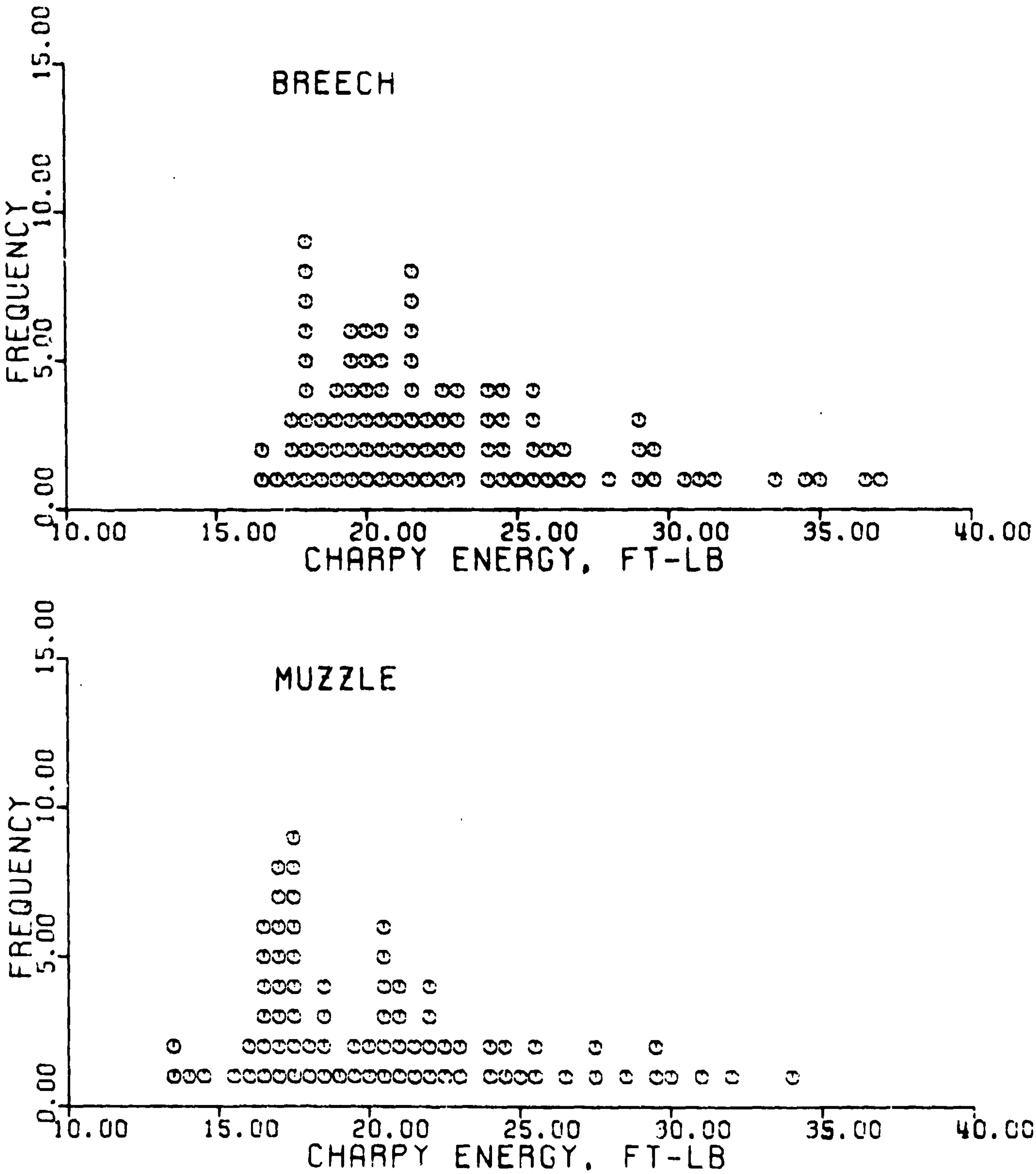

Figure 4. Frequency Versus Charpy Energy From Cannon Forgings; Muzzle and Breech Locations; ft-lb x 1.36 = Nm.

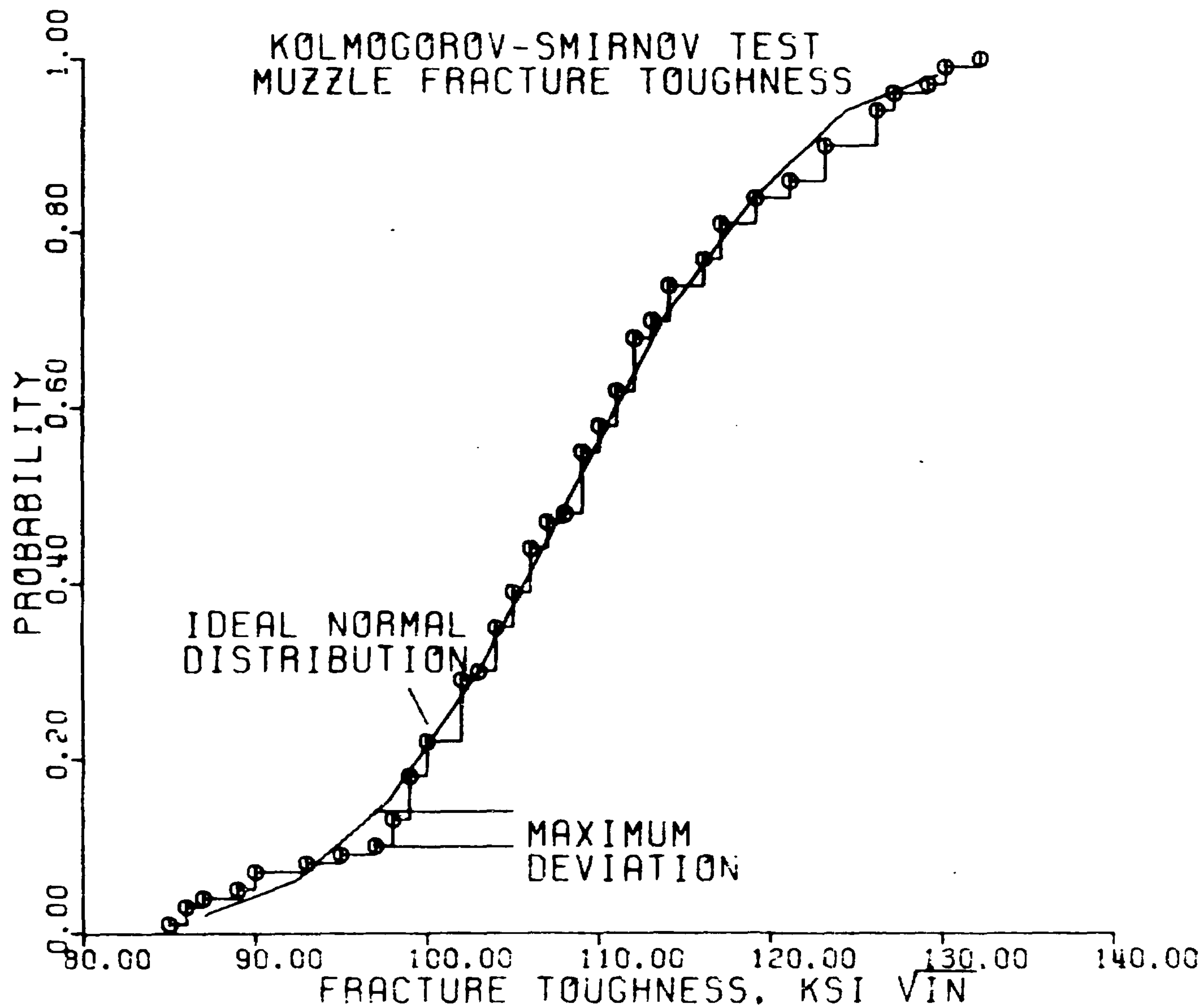

Figure 5. Probability Versus Fracture Toughness From Cannon Forgings; Muzzle Location; ksi·in.$^{1/2}$ x 1.10 = MPa·m$^{1/2}$.

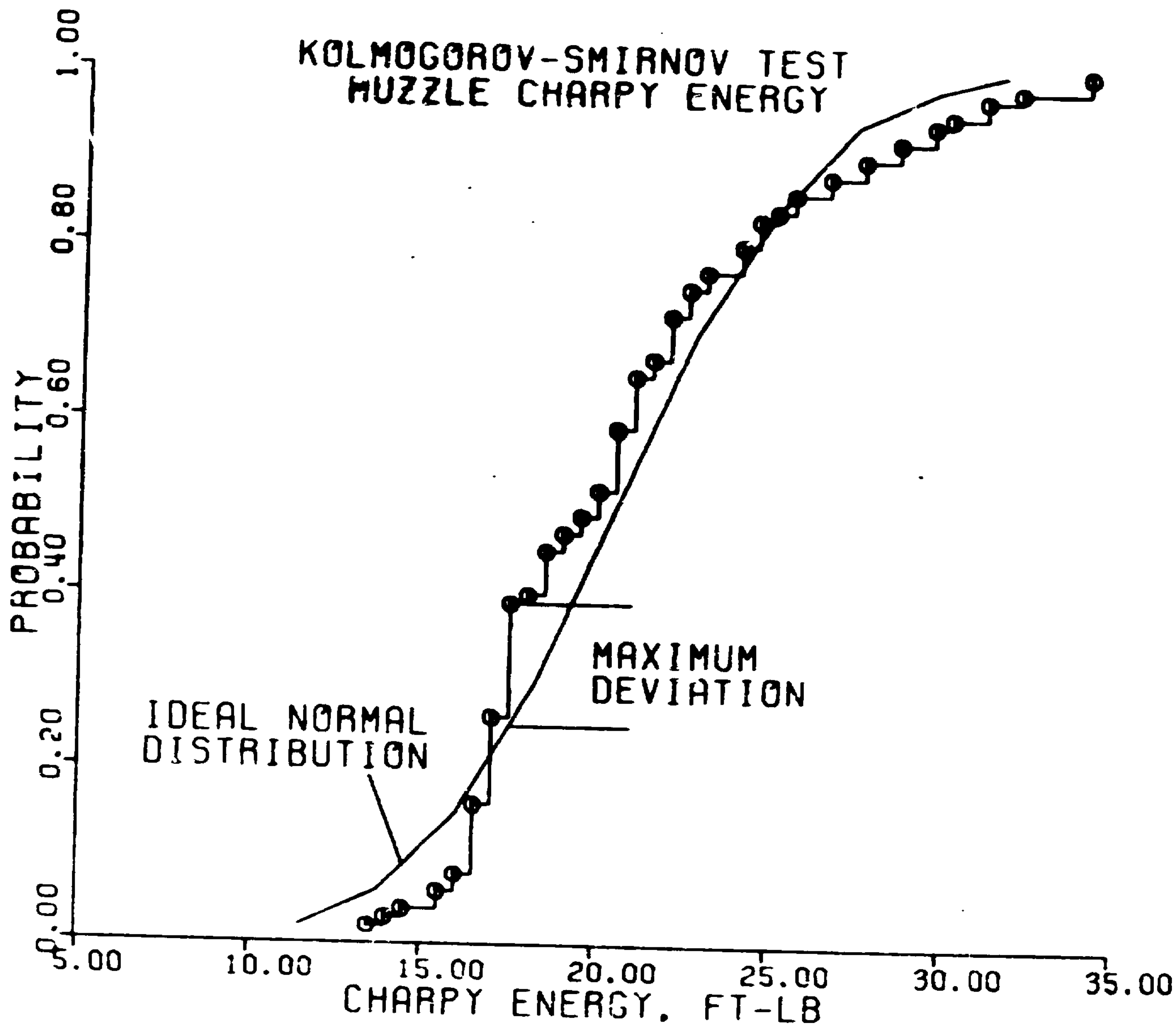

Figure 6. Probability Versus Charpy Energy From Cannon Forgings; Muzzle Location; ft-lb x 1.36 = Nm.

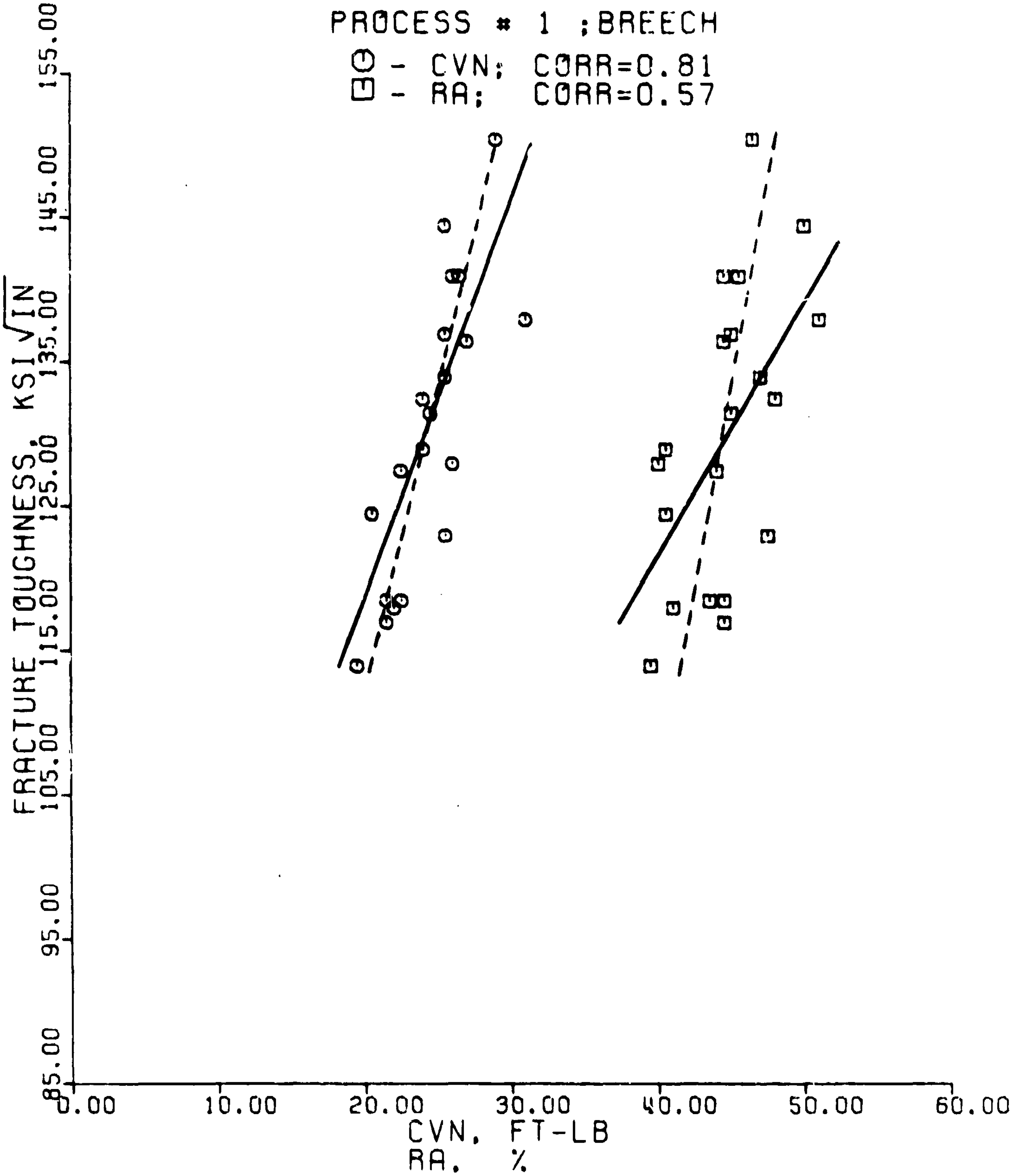

Figure 7. Fracture Toughness Versus Charpy Energy, CVN and Reduction-in-Area, RA; Breech Location; Process #1; ksi•in.$^{1/2}$ x 1.10 = MPa•m$^{1/2}$, ft-lb x 1.36 = Nm.

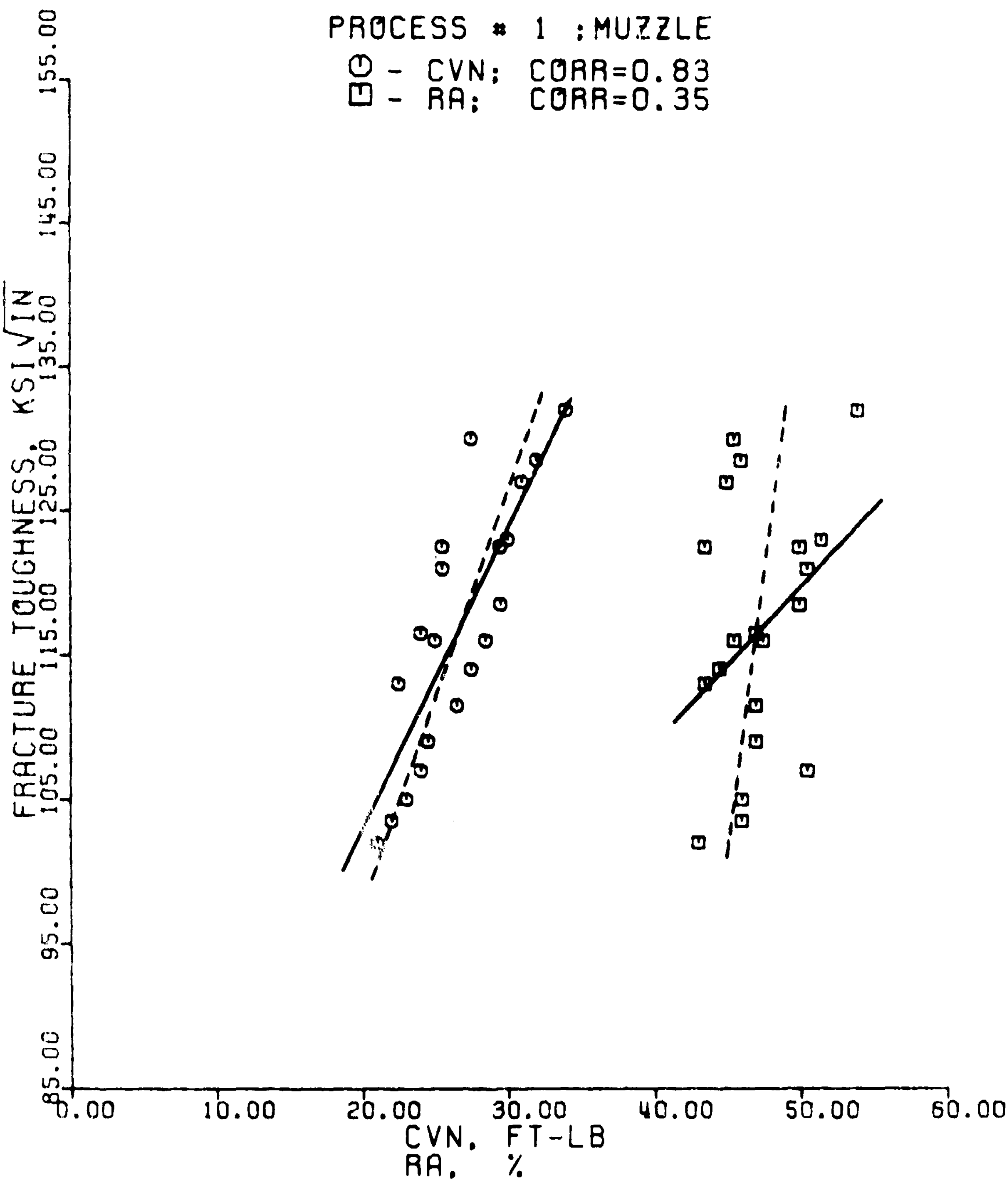

Figure 8. Fracture Toughness Versus Charpy Energy, CVN and Reduction-in-Area, RA; Muzzle Location; Process #1; ksi·in.$^{1/2}$ x 1.10 = MPa·m$^{1/2}$, ft-lb x 1.36 = N·.

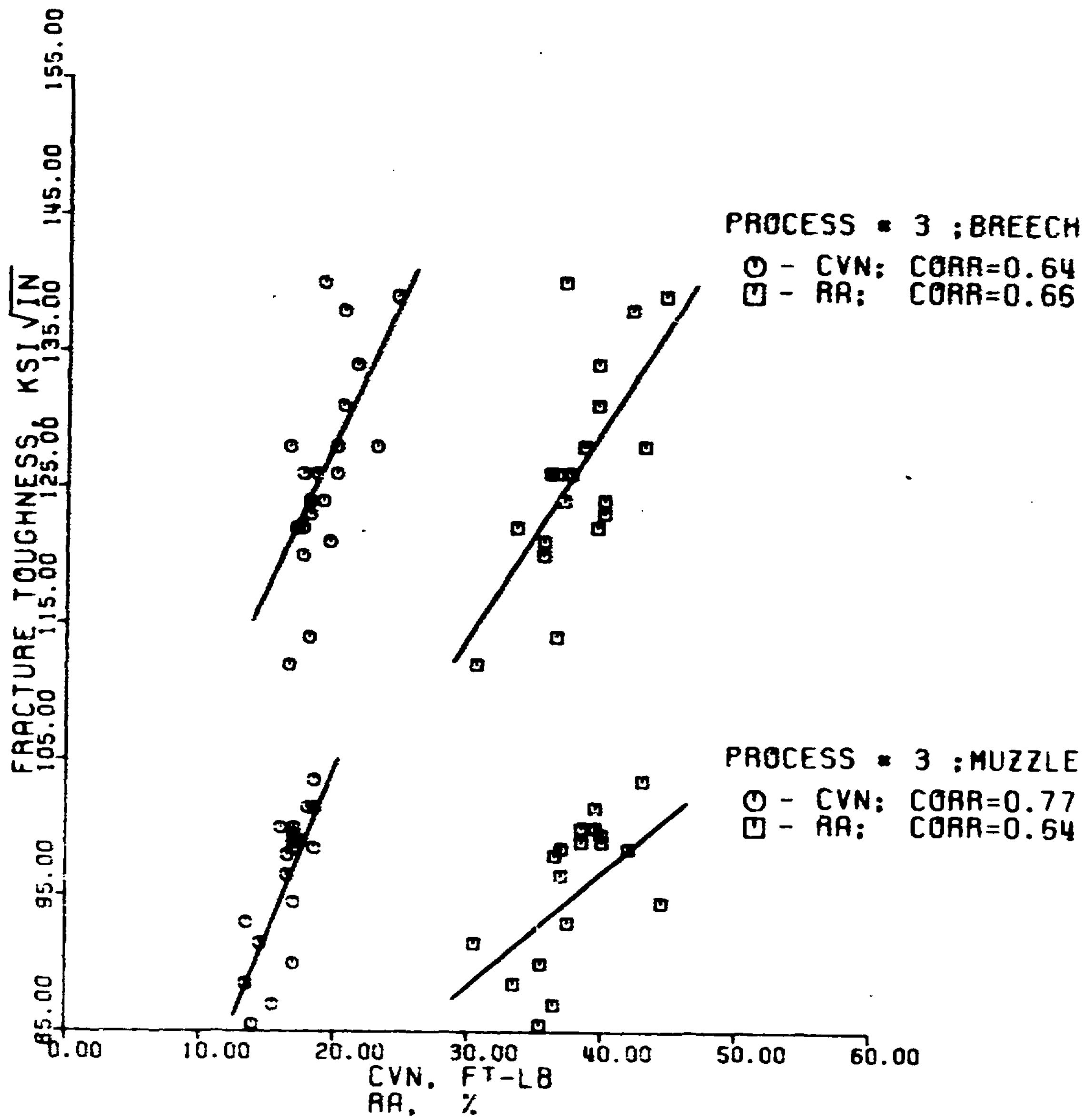

Figure 9. Fracture Toughness Versus Charpy Energy, CVN and Reduction-in-Area, RA; Muzzle and Breech Locations; Process #3; ksi·in.$^{1/2}$ x 1.10 = MPa·m$^{1/2}$, ft-lb x 1.36 = Nm.

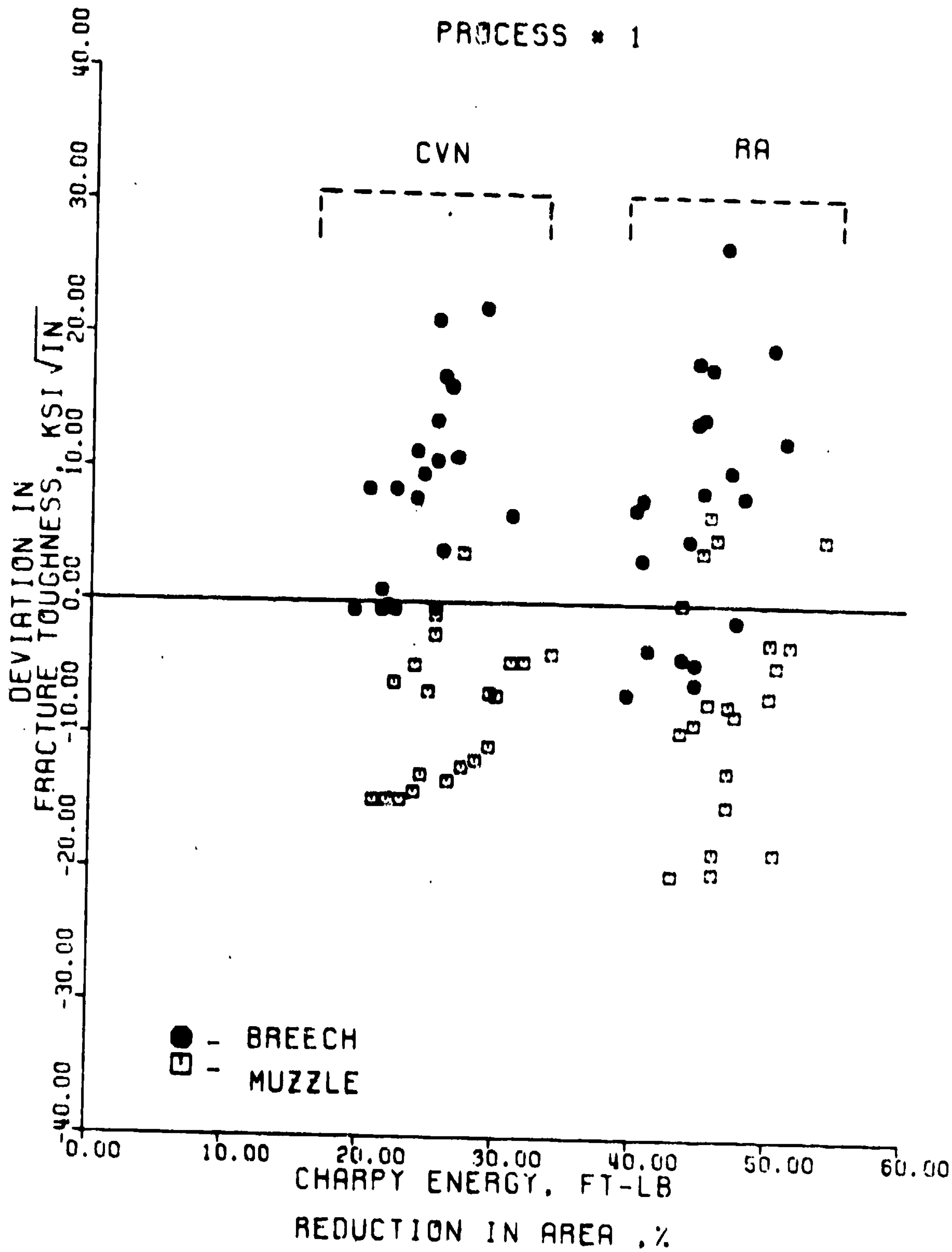

Figure 10. Deviation in Fracture Toughness Data From Regression Line Versus Charpy Energy, CVN, and Reduction-in-Area, RA; Breech and Muzzle Locations; Process #1, ksi·in.$^{1/2}$ x 1.10 = MPa·m$^{1/2}$, ft-lb x 1.36 = Nm.

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